DESIGN AND OPTIMISATION OF THREE-PHASE SALIENT ROTOR WOUND FIELD FLUX SWITCHING MOTOR

FAISAL KHAN

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Universiti Tun Hussein Onn Malaysia

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This dissertation is dedicated to my parents, my wife, my brother, and sisters, who have always encouraged me with their love and prayers.

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ABSTRACT

Permanent magnet-free wound field flux switching machine (WFFSM) with a segmented rotor and non-overlapping windings is an attractive alternative for driving high torque density applications due to their low cost, high efficiency, high average torque and power. However, a rotor with segments makes the motor less robust and difficult to be assembled, while WFFSM with salient rotor and overlapping windings inherit high copper losses and less efficiency due to their long end-windings. This thesis deals with a novel structure of WFFSM employing a salient rotor with non-overlapping field and armature windings on the stator and a presentation of an unexcited rotor. The non-overlapping winding arrangement on the stator consumes less copper material, thus improves the efficiency. Moreover, the salient rotor structure with high mechanical strength is suitable for high-speed operation. The design restrictions and specifications of the proposed motor are keep similar as WFFSM with a segmented rotor. The JMAG-Designer ver.14.1 was used to verify the motor's operating principle and performance characteristics. Three-phase configurations of WFFSM with non-overlap windings and salient rotor were studied, from the design features to performance analysis. For the three-phase operation, 11 topologies were feasible when employing a 12-tooth and 24-tooth stator. The subsequent optimisation work carried out using deterministic optimisation approach and Genetic Algorithm (GA) method to achieve the target average torque of 25.8 Nm and power of 6.49 kW. Designed and analysed by 2D and 3D finite element analysis (FEA), the optimised 12S-10P configuration had achieved high torque and power of 4.6% and 4.8% respectively, as compared to 12S-8P WFFSM with segmental rotor and non-overlapping windings. Moreover, the torque and power of the optimised design were also greater than 12S-8P WFFSM with salient rotor and overlapping windings. The 12S-14P topology had produced high average torque and power at low armature and field currents compared with all designs.

ABSTRAK

Mesin fluks beralih medan-belitan tanpa magnet kekal (WFFSM) dengan pemutar bersegmen dan belitan tidak bertindih adalah alternatif yang menarik terhadap aplikasi yang memerlukan ketumpatan tork yang tinggi. Ini disebabkan oleh kos yang rendah, kecekapan, tork dan kuasa purata yang tinggi. Walau bagaimanapun, pemutar bersegmen menjadikan motor kurang teguh serta sukar untuk dipasang, manakala, WFFSM dengan pemutar menonjol dan belitan bertindih menyebabkan kerugian pada penggunaan tembaga yang tinggi dan kecekapan yang kurang akibat daripada penghujung belitan yang panjang. Tesis ini berkaitan struktur baru WFFSM menggunakan pemutar menonjol yang mempunyai medan dan angker tanpa belitan bertindih pada pemegun dan pemutar yang tidak teruja. Susunan penggulungan tidak bertindih pada pemegun yang menggunakan kurang bahan tembaga, sekaligus mampu meningkatkan kecekapan. Selain itu, struktur pemutar menonjol dengan kekuatan mekanikal yang tinggi adalah sesuai untuk operasi mesin pada kelajuan tinggi. Had rekabentuk dan spesifikasi motor yang dicadangkan adalah masih sama seperti WFFSM dengan pemutar bersegmen. Perisisan JMAG-Designer versi 14.1 telah digunakan untuk mengesahkan prinsip operasi dan prestasi motor. Konfigurasi tiga fasa WFFSM dengan belitan tidak bertindih dan pemutar menonjol telah dikaji, bermula dengan ciri-ciri rekabentuk sehingga analisis prestasi. Bagi operasi tiga fasa, 11 topologi telah dilaksanakan apabila menggunakan 12-gigi dan 24-gigi pemegun. Kerja-kerja pengoptimuman berikutnya dijalankan menggunakan pendekatan pengoptimuman berketentuan dan kaedah algoritma genetik (GA) untuk mencapai sasaran tork purata 25.8 Nm dan kuasa 6.49 kW. Setelah mesin direka dan dianalisis menggunakan kaedah 2D dan 3D analisis unsur terhingga (FEA), konfigurasi 12S-10P yang telah dioptimumkan telah mencapai tork yang tinggi dan kuasa sebanyak 4.6% dan 4.8% masing-masing, berbanding 12S-8P WFFSM dengan pemutar bersegmen dan belitan tidak bertindih. Selain itu, tork dan kuasa rekabentuk yang

dioptimumkan juga lebih tinggi daripada 12S-8P WFFSM dengan rotor menonjol dan belitan bertindih. Topologi 12S-14P telah menghasilkan tork purata dan kuasa yang tinggi pada arus angker dan arus medan yang rendah berbanding dengan keseluruhan rekabentuk motor.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

η	-	Efficiency
ϕ	-	Flux
Ψ_{exc}	-	Flux linkage due to field excitation
θ	-	Electrical angular position of rotor
ω_r	-	Rotational speed
ρ	-	Copper resistivity
α_{cog}	-	Electrical angle of rotation for each period of cogging torque
α_f	-	Filling factor
B	-	Magnetic flux density
F	-	Magnetomotive force
f_e	-	Electrical frequency
f_m	-	Mechanical rotation frequency
i_a	-	Armature current
i_d	-	d-axis current
i_q	-	q-axis current
i_f	-	Field current
J_a	-	Armature current density
J_e	-	Field current density
k	-	Natural number
ℓ	-	Stack length

N	-	Number of turns
N_p	-	Number of periods
N_r	-	Number of rotor poles
N_s	-	Number of stator slots
P_c	-	Copper loss
P_i	-	Iron loss
P_{mech}	-	Mechanical power
q	-	Number of phases
R_U	-	Armature winding resistance per phase
$\Re$	-	Reluctance
S_a	-	Slot area
T_L	-	Load torque
CAD	-	Computer Aided Design
CNC	-	Computer Numerical Control
HE	-	Hybrid Excitation
EV	-	Electric Vehicle
FSM	-	Flux Switching Motor
FE	-	Field Excitation
FEC	-	Field Excitation Coil
FEA	-	Finite Element Analysis
GA	-	Genetic Algorithm
HEV	-	Hybrid Electric Vehicle
IPMSM	-	Interior Permanent Magnet Synchronous Motor
MEC	-	Magnetic Equivalent Circuit
SalRoN	-	Salient Rotor and Non-overlapping windings
SalRO	-	Salient Rotor and Overlapping windings
SegRoN	-	Segmental Rotor and Non-overlapping windings
WFFSM	-	Wound Field Flux Switching Machine
WFSM	-	Wound Field Synchronous Machine

LIST OF APPENDICES

LIST OF PUBLICATIONS

Journals:

(i) Faisal Khan, Erwan Sulaiman, Md. Zarafi Ahmad, "Review of Switched Flux Wound-Field Machines Technology," IETE Technical review, accepted, DOI:10.1080/02564602.2016.1190304, 2016. (ISI, Scopus, Q2, IF: 1.30)

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LIST OF AWARDS

(i) **Gold Medal** in Seoul International Invention Fair, South Korea, [SIIF 2014]: Erwan Sulaiman, Faisal Khan, Zhafir Aizat, Mubin Aizat, Sharifah Binti Saon, "Field Excitation Flux Switching Motor".

(ii) **Silver Medal** at Malaysia Technology Expo, Kuala Lumpur, [MTE 2014]: Erwan Sulaiman, Faisal Khan, Zarafi Ahmad, Zhafir Aizat "12Slot-10Pole Field Excitation Flux Switching Motor for Hybrid Electric Vehicles".

(iii) **Bronze Medal** at Research & Innovation Festival, UTHM, [R & I 2013]: Erwan Sulaiman, Faisal Khan, Zarafi Ahmad, Zhafir Aizat "Field Excitation Flux Switching Motor for Hybrid Electric Vehicles".

(iv) **Silver Medal** at Malaysia Technology Expo, Kuala Lumpur, [MTE 2015]: Erwan Sulaiman, Mohd. Fairoz Omar, Faisal Khan, Hassan Ali Soomro, Kamaluddin Hassan, "LoCo FEFS motor".

(v) **Copyright No. LY2015000027**, Erwan Sulaiman, Faisal Khan "Wound Field three-phase Flux Switching Motor with Non-overlap Winding and Salient Rotor for Hybrid Electric Vehicles".

(vi) **Industrial Design No. 14-01422-0101**, Erwan Sulaiman, Faisal Khan "12Slot-10pole Wound Field three-phase Flux Switching Motor with Non-overlap Winding and Salient Rotor for Hybrid Electric Vehicle".

(vii) **FRGS MOE Grant Vot. 1508,** "Characteristic investigations of a New Field Excitation Flux Switching Machine using Finite Element Analysis for Electric Vehicles".

(viii) Participated in **3 minutes PhD thesis competition**, 2015 at national level held at Kuala Lumpur, organised by UTM.

(ix) **Patent File No. PI2016000833,** Erwan Sulaiman, Faisal Khan, "Salient Rotor Non-Overlapping Wound Field Flux Switching Motor"

(x) **3rd Prize** in postgraduate poster competition**,** 2015 at UTHM.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Nowadays, a majority of industrial and domestic applications require more compact, more efficient, robust, light weight, and low-cost electric motors. As electric motors are the core of both industrial and domestic appliances, there is a pressing need for researchers to develop advanced electric motors. Latest research has made them literally invisible, installed within thousands of everyday products. They can be found in hybrid electric vehicles, fan, washing machine, air conditioners, vacuum cleaner, aerospace application, and rigid disc drives [1]. There are several classes of electric motors with standardised dimensions and characteristics. The development of the flux switching motor (FSM) [2], a new class of brushless motor is as recent as just over a decade ago. All the excitation sources of FSMs are located on the stator, providing simpler cooling options, while the rotor consists of only a single piece iron, neither magnet nor windings. FSMs are considered to be the most promising electric motor with high efficiency, easy thermal management, robust rotor structure, light weight, and cost-competitive. In addition, FSMs have been effectively applied to domestic and industrial applications [3-6].

FSM is a combination of a switched reluctance motor and an inductor alternator [7-8]. FSM can be categorised into three groups based on the method of excitation to stator: (1) Permanent Magnet (PMFSM), (2) Field Excitation (FEFSM), and (3) Hybrid Excitation (HEFSM). PM and field excitation coil (FEC) are the main sources of flux in PMFSM and FEFSM respectively while for HEFSM, both PM and FEC generate the flux [9-11]. Recently, the research work on PMFSM is dominated

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